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13 ABSTRACT (MAX 200 WORDS): THE PAPER EXAMINES THE DEVELOPMENT OF MICROSTRUCTURAL DAMAGE IN A GLASS REINFORCED POLYMER (GRP) LAMINATE WHEN IT IS SUBJECTED TO EXPLOSIVE SHOCK LOADING IN WATER. GRP IS COMMONLY USED IN THE SMALL NAVAL VESSELS, AND MAY BE SUBJECTED TO UNDERWATER EXPLOSIONS. IN THE EXPERIMENTS, THE LAMINATES WERE EXPOSED TO INCREASING LEVELS OF SHOCK LOADING PRODUCED BY UNDERWATER EXPLOSIONS. THE LAMINATES WERE BACKED WITH EITHER WATER OR AIR TO MODIFY THE AMOUNT OF BENDING THE GRP LAMINATE EXPERIENCED UNDER LOADING, WITH THE AIR-BACKED LAMINATES HAVING A HIGHER AMOUNT OF BENDING. EXAMINATION OF THE GRP MICROSTRUCTURE BY OPTICAL AND SCANNING ELECTRON MICROSCOPY AFTER SHOCK TESTING FAILED TO REVEAL ANY DAMAGE TO EITHER THE POLYMER MATRIX OR GLASS FIBRES WHEN THE LAMINATE WAS BACKED WITH WATER. IN CONTRAST, WHEN THE LAMINATE WAS BACKED WITH AIR, SMALL CRACKS WERE PRODUCED IN THE POLYMER MATRIX AT LOW SHOCK PRESSURES. RAISING THE SHOCK PRESSURE ABOVE THE THRESHOLD LIMIT CAUSED COMPLETE FAILURE OF THE LAMINATE BY CRACKING IN THE POLYMER MATRIX, CRACKING OF THE GLASS FIBRES, AND DELAMINATION OF THE GLASS FIBRES FROM THE POLYMER. THE DIFFERENCES IN THE SHOCK RESISTANCE OF THE WATER- AND AIR-BACKED GRP ARE DISCUSSED. MEASUREMENTS OF THE RESIDUAL TENSILE FRACTURE STRENGTH OF THE LAMINATES AFTER SHOCK LOADING ARE ALSO PRESENTED. THE FRACTURE STRENGTH OF THE WATER-BACKED LAMINATE WAS NOT AFFECTED BY SHOCK, BUT THE FRACTURE STRENGTH OF THE AIR-BACKED LAMINATE DETERIORATED WITH THE ONSET OF GLASS FIBRE BREAKAGE AND DELAMINATION IN THE GRP MICROSTRUCTURE.			
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THE DAMAGE AND FAILURE OF GRP LAMINATES BY UNDERWATER EXPLOSION SHOCK LOADING

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SUMMARY This paper examines the development of microstructural damage in a glass reinforced polymer (GRP) laminate when it is subjected to explosive shock loading in water. GRP is commonly used in the small naval vessels, and may be subjected to underwater explosions. In the experiments, the laminates were exposed to increasing levels of shock loading produced by underwater explosions. The laminates were backed with either water or air to modify the amount of bending the GRP laminate experienced under loading, with the air-backed laminates having the higher amount of bending. Examination of the GRP microstructure by optical and scanning electron microscopy after shock testing failed to reveal any damage to either the polymer matrix or glass fibres when the laminate was backed with water. In contrast, when the laminate was backed with air, small cracks were produced in the polymer matrix at low shock pressures. Raising the shock pressure above a threshold limit caused complete failure of the laminate by cracking in the polymer matrix, cracking of the glass fibres, and delamination of the glass fibres from the polymer. The differences in the shock resistance of the water- and air-backed GRP are discussed. Measurements of the residual tensile fracture strength of the laminates after shock loading are also presented. The fracture strength of the water-backed laminate was not affected by shock, but the fracture strength of the air-backed laminate deteriorated with the onset of glass fibre breakage and delamination in the GRP microstructure.

1 INTRODUCTION

Glass-fibre reinforced polymer (GRP) laminates consist of glass fibres embedded in a polymer matrix. These materials are ideal for building the hull and superstructure of marine vessels because they are relatively easy to fabricate, are not prone to corrosion or degradation by marine organisms, and have light weight combined with high strength and stiffness. The United States built the first fibre-glass naval vessels in 1947 which were small boats with a hull length of only 8.5 metres (1,2). GRP was not used in larger naval ships (up to 40 metres) until the late 1960s when the Royal Navy built *HMS Wilton* as a mine counter measures vessel (MCMV) for locating mines lying on the seabed (mine hunting) and sweeping for proximity and contact mines (mine sweeping) (3). Before this, most MCMVs were built from wood, but GRP was found to be a suitable replacement material because it is non-magnetic, and therefore is less likely to detonate magnetic mines, and it also has a low radar cross-section, making the vessel difficult to detect by radar (4). GRP is also used in selected applications on some naval submarines, and in surface vessels is used in many non-structural applications, including antenna, radomes, sonar domes, masts and propeller blades (2,4). Over the past 25 years GRP has been used increasingly in MCMVs and patrol boats, and at present about 100 naval vessels throughout the world have been built with GRP (5). The Royal Australian Navy first used GRP in the mid-1980s when it built two Bay class minehunter vessels, *HMAS Rushcutter* and *HMAS Shoalwater*. The hulls of these ships were fabricated using a foam sandwich construction. The core was rigid PVC foam and the inner and outer skins were 7 mm thick GRP (6).

The greatest threat to MCMVs during war is the explosion of underwater mines, which can cause severe structural damage to the hull. Despite the fact that GRP has been used in MCMVs for many years, it is surprising that little work appears to have been performed to gain an understanding of the detailed response of GRP to the underwater shock loading produced by submerged mines (7-9). For example, as part of the developmental work for the Australian Bay class mine hunters, the resistance of the GRP/foam sandwich material to underwater blast damage was studied, but detailed assessment of the damage morphology was not made (7). In these tests, samples of the sandwich material were subjected to underwater blasts of different levels, and then the samples were simply classified as having either passed or failed by visual inspection. Only a small amount of work was performed to study the different types of structural damage within the foam core material and delamination at the foam/GRP interface, how these types of damage were formed, and what effects the damage may have on the mechanical properties of the material.

This paper describes the response of GRP laminates when exposed to shock produced by underwater explosions. The loading conditions were varied from low shock levels, where little structural damage to the GRP was expected, to very high levels, where complete failure was expected. The effect of backing the GRP with either air or water on the amount of damage was also examined, and the residual tensile fracture strength of the laminates after being exposed to underwater blast was measured.

2 EXPERIMENTAL TECHNIQUES

2.1 Materials

The GRP laminates were made from E-type glass fibres in a vinyl ester resin. The glass fibres were in the form of either chopped strand mat (CSM) or woven roving (WR). The CSM consisted of short glass fibres, usually less than about 5 cm in length, randomly oriented across the mat. The WR was made from continuous glass fibres woven in a plain weave. The laminate contained alternating plies of the WR and CSM to a total of 14 layers, with the top ply of the laminate being WR and the bottom ply being CSM. This stacking sequence and the types of glass fibres were the same as those used in the GRP skins of the Bay class minehunter. The vinyl ester resin, known commercially as Derakane 411, was applied to the glass by hand (see Smith (4) for further details about this laminating technique), and cured at room temperature. The average resin content in the GRP was measured to be $51.3 \pm 1.7\%$ by weight, and the thickness of the laminates was between 7 and 9 mm.

To examine the effect of the vinyl ester resin on the shock response of the GRP, unreinforced resin specimens were made without any glass fibres. These polymer specimens had a thickness of about 8 mm.

2.2 Experimental Techniques

2.2.1 Underwater Explosion Shock Testing

The underwater shock tests were performed to simulate the conditions experienced by the GRP hull of a naval vessel when subjected to an underwater blast from an exploding mine, bomb or torpedo. The tests were performed in a water-filled pit which is shown schematically in Figure 1.

This small-scale shock testing facility consists of a steel cylinder confined within a concrete slab. The inside steel lining of the pit was covered with a thin plastic sheet containing small air bubbles, which was used to minimise the internal reflection of shock waves from the pit wall following the explosion (10). The pit has a diameter of 1.85 m and a depth of 2.0 m. GRP laminates were cut into rectangular specimens with a length of 270 mm and a width of 70 mm for testing. The laminates were placed at the bottom of the pit, and were clamped at each end between two sheets of rubber which allowed the GRP to bend under shock loading, as shown in Figure 1. The laminates were backed with either air or water.

The explosive charges were made from Plastic Explosive type 4 (PE4), which is composed of about 88% RDX (cyclotrimethylenetrinitramine) and 12% of a non-explosive binder, and it produces an underwater shock wave pressure which is about 15% higher than TNT (11). The weight of the explosive charges (W) were between 5.8 and 300 grams, and the stand-off distance (D) between the explosive charge and GRP was varied between 0.3 and 1.3 m. The maximum pressure of the shock wave (P_{\max}) is related to the charge weight and stand-off distance by the expression:

$$P_{\max} \approx 53.9 \left(\frac{W^{0.33}}{D} \right)^{1.13}$$

Therefore, in the experiments shock waves were generated with maximum pressures between 8 and 133 MPa. The unreinforced polymer specimens were tested with PE4 charges weighing 5.8 grams, and the stand-off distance was varied between 0.3 and 1.3 m, and this produced maximum shock wave pressures between 8 and 31 MPa.

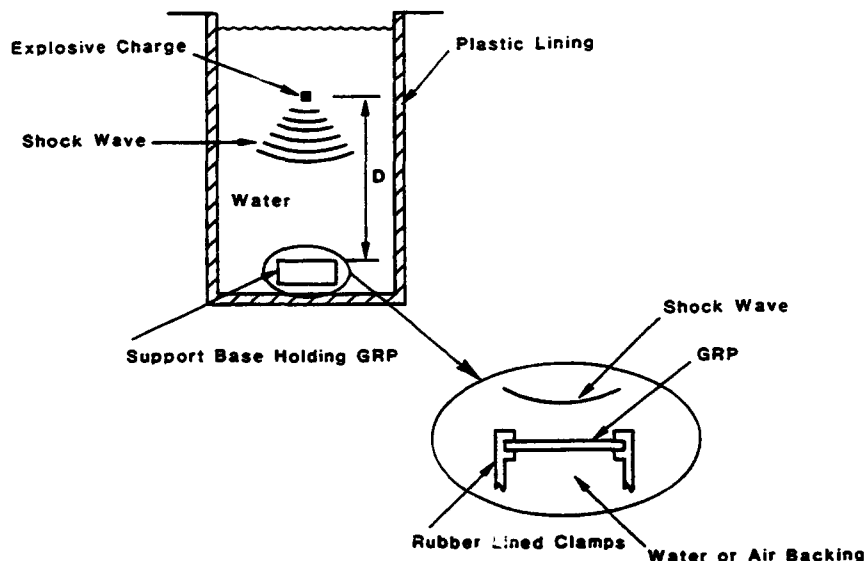


Figure 1. A schematic representation of the facilities for the underwater explosive shock testing of the GRP laminates and unreinforced polymer specimens.

2.2.2 Tensile Testing

After shock testing the rectangular specimens were machined into 'hour-glass' shaped specimens to the dimensions shown in Figure 2.

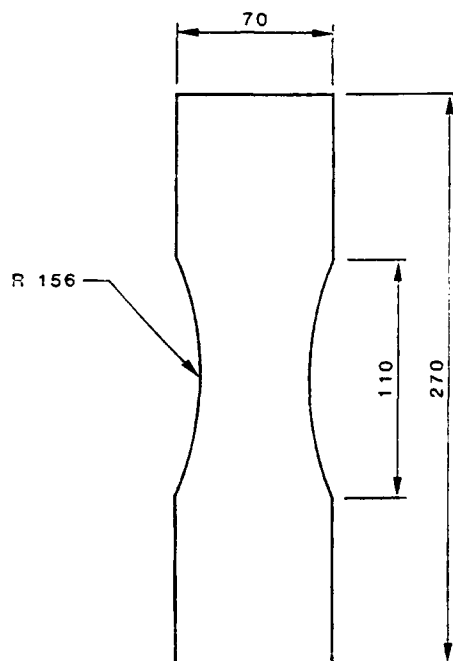


Figure 2. The dimensions of the tensile test specimens. All dimensions in mm.

The tensile tests were performed using a Riehle testing machine at a strain rate of about $25 \times 10^{-6} \text{ s}^{-1}$, and a continuous record of the stress-strain behaviour was obtained up to failure.

3 RESULTS

3.1 Shock Damage to the GRP Laminates and Unreinforced Polymer

Figure 3 shows a typical pressure against time profile for an underwater shock wave striking a GRP laminate. This profile was recorded by a pressure gauge positioned at a stand-off distance (D) of 1.1 m from a 300 gram explosive charge. The rapid rise in pressure at the start of the profile represents the front of the shock wave striking the GRP. In this case the maximum pressure (P_{max}) of the shock wave front was measured to be 31 MPa. As the wave passes through the laminate its pressure is seen to decrease rapidly with time to zero at $\sim 0.29 \text{ ms}$. Following the initial shock front, a series of smaller pressure spikes are observed after 0.48 ms, and these result from internal reflections of the shock wave within the water-filled pit. In all of the shock tests similar pressure-time profiles to that shown in Figure 3 were recorded. The only difference was that the stand-off distance was varied to produce maximum shock wave pressures between 8 and 133 MPa.

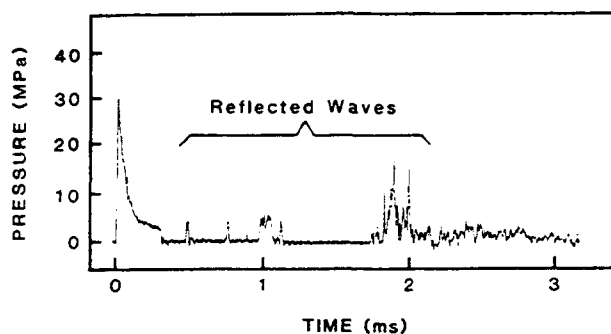


Figure 3. An underwater pressure against time profile measured for a 300 gram explosive at a stand-off distance of 1.1 m. The first large pressure spike, which occurs between times 0 and 0.29 ms, is the shock wave while the smaller pressure spikes occurring at times after 0.48 ms result from the internal reflections of the shock wave off the pit wall and floor.

Following the shock tests the GRP laminates were sectioned, polished and etched to study any microstructural damage. When the laminates were backed with water they showed no evidence of damage, even under the highest maximum shock pressure of 133 MPa. In comparison, the air-backed laminates showed considerable damage, with the extent and density of damage increasing with the shock pressure. At the lowest shock pressures studied ($< 8 \text{ MPa}$), the only evidence of damage to the GRP was fine cracking in the resin matrix, as shown in Figure 4.

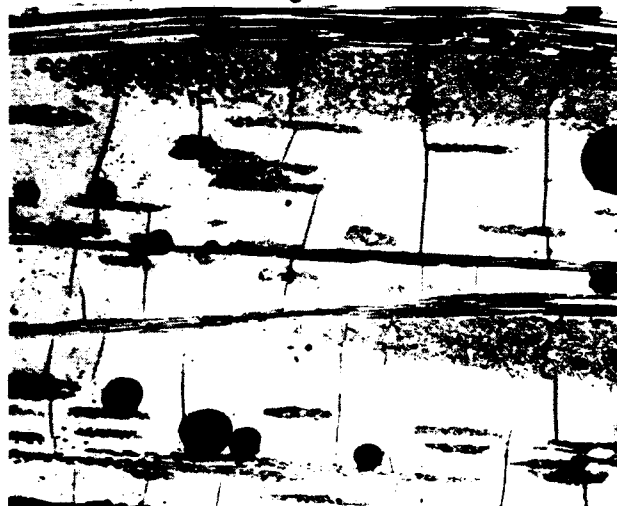


Figure 4. An optical micrograph showing cracks in the resin of GRP after being shock tested.

In Figure 4 it can be seen that the glass fibres were not broken under these shock loading conditions. The resin cracks were always close to the rear surface of the laminate; opposite the front surface which was struck by the shock wave. As shown in Figure 4, the cracks almost always occurred between the glass ply layers, and therefore cracking was normal to the rear surface of the laminate. When the resin cracks encountered the glass plies one of two things

happened depending upon the orientation at the fibres. For cases when the fibres were normal to the crack trajectory they either stopped the crack or changed its direction. This is exemplified by Figure 5, which shows that when the crack reached the fibre, it changed direction by 90° and travelled along the interface between the glass and resin. The second aspect of crack behaviour concerned the crack path which was observed to weave between the glass fibres, as shown in Figure 6.

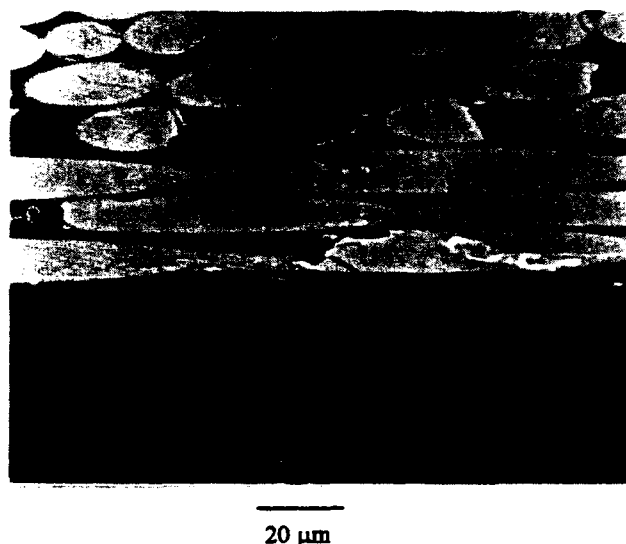


Figure 5. A scanning electron micrograph showing a crack in the resin being stopped at a glass fibre.

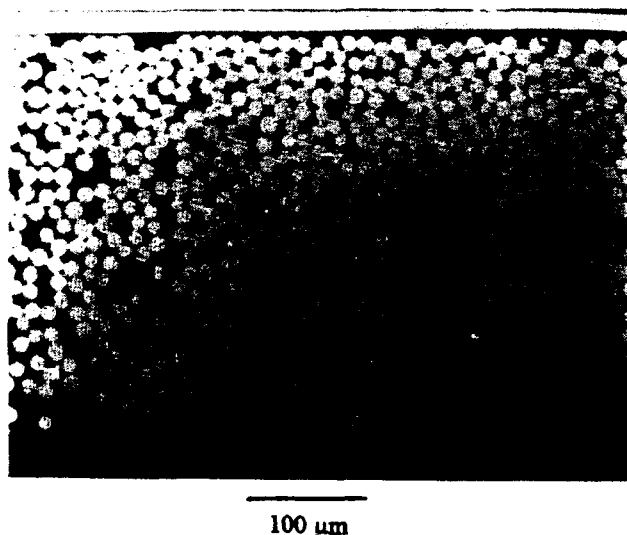


Figure 6. A scanning electron micrograph showing a crack in the resin weaving between the glass fibres.

At peak shock pressures above 11 MPa the laminates were permanently deformed or broken. In these cases, resin cracking was also observed towards the rear surface. Measurements of the resin crack size and crack density were made on sections cut from the centres of the laminates, which were then polished and etched in dilute hydrofluoric acid. This method revealed an increasing incidence of cracking as the shock pressure was increased. For example,

raising the maximum pressure from 31 MPa to 57 MPa increased the density of resin cracks observed on the polished surfaces from $0.8 \times 10^6 \text{ m}^{-2}$ to $2.2 \times 10^6 \text{ m}^{-2}$, respectively. Figures 7a and 7b present histograms of crack size against number of cracks for the GRP after being tested at maximum shock pressures of 31 MPa and 57 MPa, respectively. For a pressure of 31 MPa, the average crack size was measured to be 0.380 mm with a maximum size of 1.0 mm. Raising the pressure to 57 MPa increased the average crack size to 0.516 mm with a maximum size of 2.4 mm. In the samples tested above 11 MPa many of the glass fibres were broken, and there was extensive delamination between the glass plies, as shown in Figure 8.

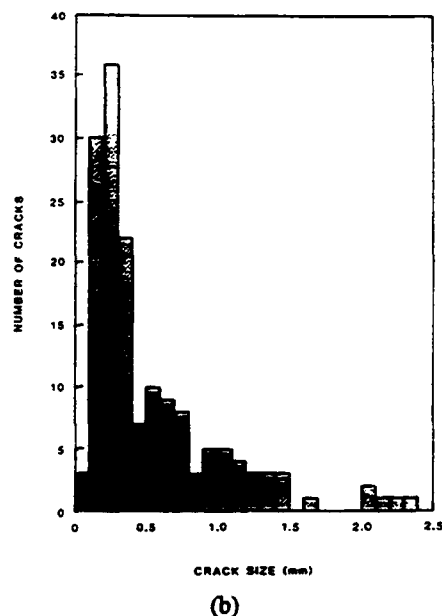
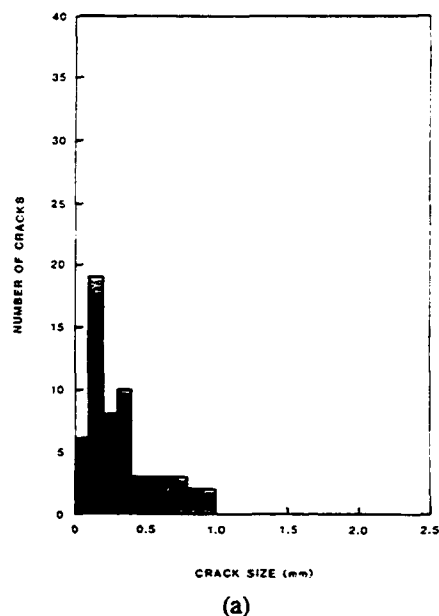


Figure 7. Histograms of crack length plotted against number of cracks for the GRP after being tested at a maximum shock pressure of (a) 31 MPa and (b) 57 MPa.

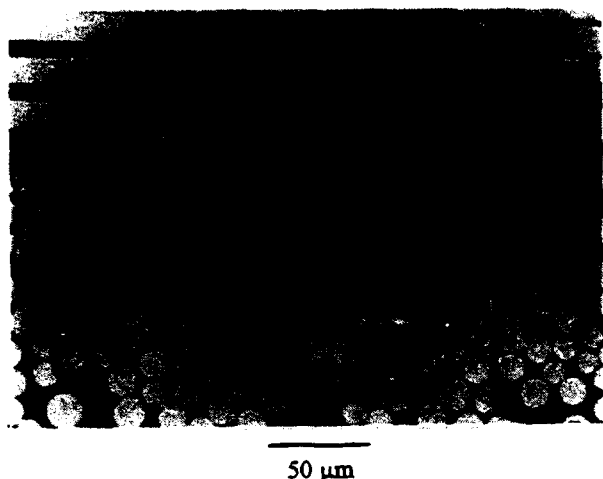


Figure 8. A scanning electron micrograph showing extensive delamination between two glass plies.

The unreinforced polymer specimens were also shock tested to evaluate the effect of the polymer matrix on the shock resistance of the GRP. It was found that when backed with water, the polymer could withstand maximum shock pressures up to ~11 MPa without showing signs of cracking or permanent deformation. Raising the shock pressure further caused the polymer to shatter into fragments, with the size of the fragments becoming progressively finer as the pressure was increased from 11 MPa.

3.2 Residual Tensile Strengths of the Shock Damaged GRP Laminates and Unreinforced Polymer

The tensile fracture stress of the laminates was measured to determine whether the underwater shock wave affected the mechanical properties. Figure 9 shows the general forms of the two types of stress-strain curves measured for the laminates.

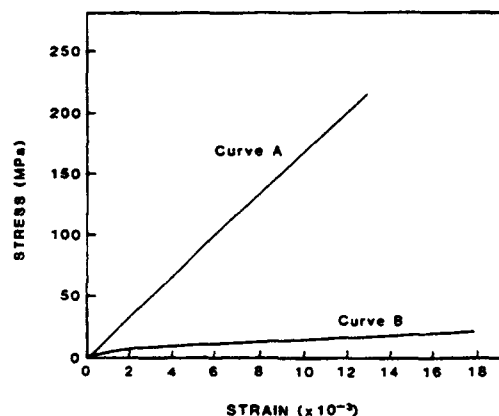


Figure 9. Stress-strain plots for the GRP laminates. The unshocked laminates, all the water-backed laminates tested up to shock wave pressures of 133 MPa, and the air-backed laminates tested at shock wave pressures below 11 MPa had stress-strain plots similar to curve A. The air-backed laminates tested at shock wave pressures above 11 MPa had stress-strain plots similar to curve B.

The stress-strain curve for the laminate before being shock tested was similar to curve A, as were the curves for all the water-backed laminates tested up to a shock wave pressure of 133 MPa and the air-backed laminates tested at shock wave pressures below 11 MPa. In each of these cases the stress-strain curve was linear up to failure, with an average stiffness (Young's modulus) of 13.5 ± 2.5 GPa. The fracture stress was between about 150 and 220 MPa. When the air-backed laminates were exposed to maximum shock pressures exceeding 11 MPa they exhibited stress-strain curves similar to curve B. The stiffness and fracture stress of these laminates were much lower than for curve A.

Figure 10 shows the tensile fracture stresses of the water-backed and air-backed laminates plotted against the maximum pressure of the shock wave.

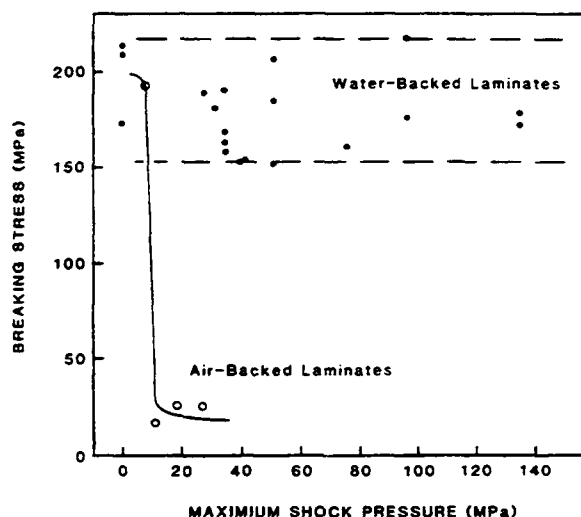


Figure 10 A plot of tensile fracture stress against maximum shock wave pressure for the GRP laminates backed with water or air.

The fracture stress of the GRP before shock testing was measured to be 200 ± 16 MPa. Over the range of shock pressures studied, the water-backed laminate showed no significant change in its fracture stress beyond the scatter in the results between 150 and 220 MPa. The fracture stress of the air-backed laminates remained relatively constant up to a shock wave pressure of 11 MPa, but at higher shock pressures the fracture stress decreased considerably down to between 15 and 30 MPa. This sudden reduction in the fracture stress corresponded to the onset of extensive glass fibre breakage and delamination. At shock wave pressures above 40-80 MPa the air-backed laminates were completely broken and so their tensile strengths could not be measured.

Tensile tests were also performed on the unreinforced polymer specimens which were not broken during shock testing. The fracture strength of the polymer before being shock tested was measured to be 41 MPa. All of the specimens which were shock tested also had a similar fracture stress, indicating that the shock does not deteriorate the tensile properties of the polymer.

The findings presented above show that when the GRP laminate was backed with air it was damaged by underwater blast. The polymer matrix suffered fine-scale cracking near the rear surface of the laminate, and these cracks extended into the GRP between the glass plies (Figure 4). When the shock wave reaches the GRP it exerts a short duration pressure pulse which bends the laminate. Cesnik (12) has used beam theory to calculate the amount of bending experienced by the air-backed laminates under static loading, and he found that it can be significant, particularly under high loads. For example, when the GRP is uniformly loaded to 30 MPa, the centre of the laminate may be deflected by about 1.2 mm from its original position. It is expected that the deflection of the laminate under shock loading will not be as great as for static loading under similar loading pressures. This is because the maximum pressure of the shock wave is exerted on the laminate for a very short period of time (typically less than a few microseconds) before the pressure decreases, as shown in Figure 3. Consequently, the laminate does not have enough time to reach the position of maximum deflection predicted for static loading conditions before the pressure from the shock wave has been reduced. Nevertheless, measurements using strain gauges of the stress distribution in the laminates have shown that they undergo some bending when subjected to an underwater shock wave, with the top surface being placed in compression and the rear surface in tension (13). It is possible that the resin cracks nucleate and grow from the rear surface towards the centre of the laminate under the presence of this tensile stress. The tensile tests performed on the unreinforced polymer revealed that its failure strength was 41 MPa. This suggests that the tensile stresses generated in the laminate as it is bent must exceed 41 MPa to cause the resin to crack. The measurements of the resin crack density showed that more cracks were produced when the maximum shock pressure was increased, with the crack density increasing from $0.8 \times 10^6 \text{ m}^{-2}$ to $2.2 \times 10^6 \text{ m}^{-2}$ when the pressure was raised from 31 to 57 MPa. Similarly, the measurements of the crack size distribution shown in Figure 7 reveal that the cracks are longer in the GRP subjected to the higher shock pressure, with the average crack size increasing from 0.380 to 0.561 mm when the pressure was raised from 31 to 57 MPa. The increased crack density and crack length results from the higher amount of bending experienced by the GRP when the shock pressure is increased, which in turn promotes a higher tensile stress at the rear surface of the laminate.

The high density of cracking induced in the resin under shock loading suggests that polymers with a high tensile strength and fracture toughness should be used in the GRP hulls of naval ships which may be exposed to underwater explosions. Studies have shown that the fracture toughness of polymers may be improved considerably by blending small rubber particles into the resin (e.g. Ref 14). These particles have a very high toughness, and either stop or deflect the cracks propagating through the polymer, which thereby raises the fracture toughness. The need to improve

the fracture toughness of the GRP used in ship hulls has already been recognised by the Singapore navy, which recently commissioned Landsort class minehunter vessels with the GRP hull made from a toughened vinyl resin. Although this is the only case where toughened polymers have been used in the GRP hulls of naval ships, increased use of toughened polymer matrices is expected.

The examination of the microstructure of the GRP after shock testing revealed that the glass fibres either stopped or deflected the cracks within the polymer matrix (Figures 5 and 6), and thereby improved the underwater shock resistance of the laminate. Furthermore, it is believed that the fibres take a large proportion of the tensile loads resulting from the bending of the laminates under shock loading. These experiments have clearly shown that the glass fibres provide most of the shock resistance, and this can be attributed to the significantly lower tensile failure strength of the polymer.

The shock tests also revealed that the water-backed laminates did not experience any damage under shock loading while the air-backed laminates suffered considerable damage, particularly at maximum shock pressure exceeding ~11 MPa. When the laminate is water-backed, there is relatively little mismatch in the impedance between the laminate and water, and consequently the shock wave passes through the laminate and continues on through the water. On the other hand, when the laminate is air-backed, there is a very large impedance mismatch between the laminate and air. As a result, the shock wave is almost entirely reflected from the rear surface of the laminate, thereby effectively doubling the shock loading.

The inability of the shock waves to damage the water-backed laminate accounts for its residual tensile fracture strength remaining unchanged as the shock pressure was increased (Figure 10). In the case of the air-backed laminate, Figure 10 shows that its fracture strength remained unaffected until the shock pressure exceeded about 11 MPa, when a sudden reduction in the fracture strength was observed. The microstructural examination of the GRP tested at pressures below 11 MPa revealed some cracking of the resin, but no damage to the glass fibres. This suggests that the cracking of the resin does not affect the tensile strength of the GRP, and this is because the glass fibres carry all of the load. At pressures above ~11 MPa, many of the fibres were broken, and this caused the large reduction in the fracture strength of the laminate.

The tensile strength measurements presented in Figure 10 show considerable scatter in the results, with the fracture stress varying between about 150 and 220 MPa. This scatter probably results from the non-uniform distribution of pores within the laminates. During the laminating process, defects are created in the laminates by small air bubbles being trapped in the polymer matrix. After curing these bubbles form pores within the polymer and along the interface between the polymer and glass fibres. The size and distribution of the pores can vary between specimens, and

this may result in the observed scatter in the tensile strength measurements.

5 CONCLUSIONS

This study of the response of GRP to underwater shock has shown that the amount of damage is considerably higher when the laminate is backed with air than with water. This is because water reduces the amount of bending of the laminate when hit by the shock wave. This bending promotes a tensile stress at the rear surface of the laminate, and this leads to cracking of the polymer matrix and in severe cases fracture of the glass fibres. The glass fibres contribute significantly to the shock resistance of the GRP by carrying almost all of the tensile load, and by either stopping or deflecting the cracks within the polymer matrix. The formation of cracks within the polymer was found to have no effect on the residual tensile fracture strength of GRP, however the strength decreased considerably with the onset of fibre breakage.

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